

# ON ELECTRO-WEAK MIXING DERIVED FROM RADIATIVE CORRECTIONS AND THE NECESSITY OF THE HIGGS MECHANISM

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**Abstract** Starting from the unmixed Lagrangian, the electro-weak radiative corrections are recomputed using symmetrical generalised functions. All gauge bosons acquire an indeterminate mass. Electro-weak mixing is obtained by diagonalization of the mass matrix. The W/Z mass ratio follows automatically. The Higgs mechanism is not needed to generate the vector boson masses. A mass sum rule is postulated to obtain a zero photon mass. The radiative corrections are different, and (provisionally) in agreement with experiment, when the no longer needed Higgs terms are omitted.

## 1. Introduction

A new theory of generalised functions has been constructed [1,2]. The available simple model allows the multiplication of all generalised functions needed in quantum field theory. Standard concepts of analysis, such as limit, derivative, and integral, have to be extended to make multiplication of generalised functions possible. Integration between arbitrary limits is always possible and yields a well-defined finite result. Infinity of integrals is replaced by the less restricted concept of determinacy, which is related to the scale transformation properties of the integrand. In contrast to all regularization schemes the results *are not arbitrary by finite renormalizations* [3].

Conversely, all results in quantum field theory that depend on the use of *any particular method of regularization* are invalid by the standard of the symmetrical theory of generalised functions. In particular, every result that is dependent on the use of dimensional regularization disagrees with the corresponding generalised function result [3]. This is not merely a mathematical nicety, it has physical consequences for observable quantities. The usual computations of the radiative corrections in the standard model found in the literature [4] are an example [5].

One should define one's mathematical tools before one starts calculating, instead of adjusting the definitions in order to obtain results supposed to be desirable. The added strength of the generalised function method comes from its requirement that all of mathematical analysis should be constructed in such a way that multiplication of generalised functions is possible, instead of fixing things up afterwards when trouble occurs.

In this paper we calculate the second order vacuum polarization in the unmixed standard model with the Higgs mechanism omitted. The gauge symmetry breaks automatically,

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and electro-weak mixing occurs inevitably, with the correct results. The idea of dynamical symmetry breaking is not new. In fact it was considered already [6,7] before the standard model became well-established. It did not meet with success however. This is understandable, using renormalization methods the necessary mathematical tools are lacking. The absence of arbitrary finite renormalizations and the irrelevance of renormalizability are essential for this purpose.

## 2. The Lagrangian

The starting point is the usual  $SU(2) \otimes U(1)$  Lagrangian, omitting the Higgs terms

$$\begin{aligned} \mathcal{L} = & -\frac{1}{4}W^{\mu\nu} \cdot W_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} + \\ & + i\bar{\psi}_L\gamma^\mu(\partial_\mu + ig_w\mathbf{W}_\mu \cdot \frac{\boldsymbol{\tau}}{2})\psi_L + i\bar{\psi}\gamma^\mu(\partial_\mu + i\frac{g'}{2}Y^w B_\mu)\psi + im_t\bar{t}t, \end{aligned} \quad (1)$$

with a vector triplet coupled with strength  $g_w$  and an isosinglet  $B$  coupled to the weak hypercharge current  $Y^w = 2Q - 2T^3$  with strength  $g'/2$ , and with the field strengths given by

$$\begin{aligned} \mathbf{W}_{\mu\nu} &= \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu - g_w\mathbf{W}_\mu \times \mathbf{W}_\nu, \\ B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu. \end{aligned} \quad (2)$$

The  $SU(2)$  symmetry is broken by hand. The top quark is given a non-zero mass, leaving the bottom quark (effectively) massless. The leptons and other generations do not contribute,

Note: It is inevitable that one fermion mass is introduced to set the mass scale. Gauge boson masses can result from radiative corrections, conversely fermion masses cannot be generated by interaction with massive gauge bosons.

We have to compute the charged  $W^{1,2}$  or  $W^\pm$  radiative corrections caused by the  $t\bar{b}$ -quark loop, and the neutral  $W^3$  and  $B$  radiative corrections from virtual  $t\bar{t}$  pairs. In addition the  $W^3$  and the  $B$  mix, since a  $W^3$  may create a  $t\bar{t}$  pair, which successively annihilates to a  $B$ , and visa versa, giving rise to three related diagrams differing only by vertex factors. It is convenient to calculate the loops with vertex factor  $c_V\gamma^\mu - c_A\gamma^\mu\gamma^5$  and specialize afterwards.

The cubic and quartic terms in  $W_\mu$ , from  $W^{\mu\nu} \cdot W_{\mu\nu}$ , give rise to a W-boson self-interaction. This is also needed to obtain physically correct radiative corrections.

Since only the mass terms have to be computed it is not necessary to consider ghosts. We can compute conveniently in the unitary gauge, which is free of unphysical fields.

## 3. Charged vector bosons

The fermionic contribution to the  $W^\pm$  self-energy is found from the boson-fermion vertex and the corresponding fermion loop diagram,

Feynman diagram to be added

which is needed for the present purpose only at boson momentum  $k = 0$ . Substitution of the Feynman rules with the general vertex factor (A3) gives

$$\Pi_{\mu\nu}(0) = -\frac{3g^2}{4} \text{Tr} \int \frac{d^4p}{(2\pi)^4} \gamma_\mu (c_V - c_A \gamma_5) \frac{\not{p} + m_1}{p^2 - m_1^2} \gamma_\nu (c_V - c_A \gamma_5) \frac{\not{p} + m_2}{p^2 - m_2^2}, \quad (3)$$

multiplied by an additional factor three for summing over the quark colours. After evaluating the trace, contracting with  $g^{\mu\nu}$ , and combining the denominators with the usual Feynman trick, one obtains

$$\Pi_\mu^\mu(0) = \frac{3g^2}{32\pi^4} \int_0^1 dx \int d^4p \frac{(c_A^2 + c_V^2)p^2 + 2(c_A^2 - c_V^2)m_1m_2}{(p^2 - xm_1^2 - (1-x)m_2^2)^2}. \quad (4)$$

For  $W^\pm$ -bosons the dominant contribution is obtained by taking the fermions to be a top and a bottom quark. To sufficient accuracy the bottom quark and all leptons are massless for the present purpose.

Substitution of  $g = g_w/\sqrt{2}$ ,  $c_V = c_A = 1$ ,  $m_1 = m_t$ ,  $m_2 = m_b = 0$ , and the value of the integrals (A1,2) from the appendix, yields

$$m_W^2 = \frac{1}{4i} \Pi_\mu^\mu(0)_{W^\pm} = -\frac{3g_w^2}{32\pi^2} m_t^2 (\log m_t^2 + C - 1). \quad (5)$$

It is seen from the appearance of an indeterminate constant  $C$  that the result is indeterminate. As usual, this means that the mass has to be supplied by experiment. Fermion loops always give rise to indeterminacy, except for the special case of vector coupling with  $m_1 = m_2$ .

Note: It is not necessary to write  $\Delta m_W^2$  here, since the W-bosons are massless to begin with by gauge invariance. The physical  $W^\pm$  mass comes entirely from the interaction with the fermion loop. This means we have skipped an order: The zero<sup>th</sup> order mass has been generated from second order perturbation theory.

#### 4. Neutral gauge bosons

The top/antitop vertex can couple left and right to a  $W^3$  or a  $B$ , giving rise to three different diagrams. (The two mixed off-diagonal diagrams are equal.) One calculation gives all three by specializing the coupling constants and  $c_A$  and  $c_V$  appropriately. The calculation proceeds as above, with  $m_1 = m_2 = m_t$  equal. The Feynman trick is not needed and the integrals evaluate directly to

$$\begin{aligned} B \cdot \frac{\bar{t}}{t} \cdot B &\rightarrow m_B^2 = \frac{1}{4i} \Pi_\mu^\mu(0)_{BB} = -\frac{3g'^2}{32\pi^2} m_t^2 (\log(m_t^2) + C - \frac{17}{18}), \\ B \cdot \frac{\bar{t}}{t} \cdot W^3 &\rightarrow m_{BW^3}^2 = \frac{1}{4i} \Pi_\mu^\mu(0)_{BW^3} = +\frac{3g'g_w}{32\pi^2} m_t^2 (\log(m_t^2) + C + \frac{1}{6}), \\ W^3 \cdot \frac{\bar{t}}{t} \cdot W^3 &\rightarrow m_{W^3}^2 = \frac{1}{4i} \Pi_\mu^\mu(0)_{W^3W^3} = -\frac{3g_w^2}{32\pi^2} m_t^2 (\log(m_t^2) + C - \frac{1}{2}). \end{aligned} \quad (6)$$

It should be noted that the numbers appearing with the indeterminate constant  $C$  are by themselves meaningless, since any finite number can be added at will. Nevertheless, by keeping them consistently, one can compute determinate differences of indeterminate quantities [1-3].

## 5. Electro-weak mixing

The vacuum polarization terms contribute a quadratic form in  $(B, W^3)$  to the effective second order Lagrangian, characterized by a (squared) mass matrix  $\mathbf{M}$ . Collecting all results gives the second order mass matrix for the neutral vector bosons

$$\mathbf{M} = -\frac{3m_t^2}{32\pi^2} \begin{pmatrix} g'^2(C - \frac{17}{18}) & -g'g_w(C + \frac{1}{6}) \\ -g'g_w(C + \frac{1}{6}) & g_w^2(C - \frac{1}{2}) \end{pmatrix} \quad (7)$$

(Temporarily omitting the  $\log(m_t^2)$  for clarity.) The  $C^2$  terms cancel in the determinant of  $\mathbf{M}$ , so only one of the  $C$ -eigenvalues can be indeterminate. The indeterminate part of  $\mathbf{M}$  is diagonalized by the transformation

$$\begin{aligned} A_\mu &= +B_\mu \cos \theta_w + W_\mu^3 \sin \theta_w, \\ Z_\mu &= -B_\mu \sin \theta_w + W_\mu^3 \cos \theta_w, \end{aligned} \quad (8)$$

with the conventional definitions

$$\tan \theta_w = \frac{g'}{g_w} \quad \text{so} \quad \sin \theta_w = \frac{g'}{g_z} \quad \text{with} \quad g_z^2 = g_w^2 + g'^2. \quad (9)$$

The neutral mass matrix is transformed by the electro-weak rotation into

$$\mathbf{M} = \frac{3m_t^2}{32\pi^2} \begin{pmatrix} g_e^2 \frac{16}{9} & g_e g_z (\frac{2}{3} - \frac{16}{9} \sin^2 \theta_w) \\ g_e g_z (\frac{2}{3} - \frac{16}{9} \sin^2 \theta_w) & -g_z^2 (C + \frac{1}{2} - \frac{4}{3} \sin^2 \theta_w + \frac{16}{9} \sin^4 \theta_w) \end{pmatrix} \quad (10)$$

By definition the indeterminate eigenvalue is assigned to the  $Z_\mu$ . It can be put equal to the experimental mass, as usual in quantum field theory.

Comparing the  $Z$ -mass and the previously found  $W$ -mass (5), one sees that both are indeterminate, but ignoring finite terms for the time being, their ratio is determinate

$$\frac{m_w^2}{m_z^2} = \frac{g_w^2}{g_z^2} = \cos^2 \theta_w + \mathcal{O} \left( g_w^2 \frac{m_t^2}{m_w^2} \right). \quad (11)$$

The radiative corrections to this equation, which have been computed already in (5) and (6) will be compared in section 8 with the standard model results.

The second order effective Lagrangian almost agrees with the standard model Lagrangian with mass terms after the Higgs rotation. It has the correct couplings and masses.

The  $A^\mu A_\mu$  element of the mass matrix must be interpreted as a finite, non-zero photon mass, in apparent disagreement with electromagnetic gauge invariance. The result agrees with a previous calculation [8] based on QED alone. It is determinate, so it must have a physical meaning.

However, the initially massless  $W$  and  $Z$  vector bosons now have acquired a mass, so it is necessary to consider also the boson self-interactions introduced by the non-Abelian group. These will contribute self-mass terms, which must be taken into account in order to be consistent. This peculiar situation is a consequence of the initial masslessness of the gauge bosons.

## 6. Vector boson self-interaction

The cubic and quartic terms in the free field part of the Lagrangian give rise to vector boson self-interaction. Massless vector bosons do not have a mass term in the self-interaction. When the vector bosons have acquired a mass (by any mechanism) there will be self-mass corrections. All self-interactions have the same structure, so we compute only need to compute the generic case, for example the  $W^3$  self-mass. The others are equal to it by cyclic permutation.

There are two Feynman diagrams contributing to the self-energy

Feynman diagram to be added

obtained from the vertices (A8,9). The 3-boson vertices give a loop diagram. One finds that the terms involving  $p^4 p_\mu p_\nu$  cancel, leaving upon contraction with  $g^{\mu\nu}$  the quartic and quadratic terms

$$\Pi_\mu^\mu(0)_{\text{loop}} = -6 \frac{g^2}{m^2} \int \frac{d^4 p}{(2\pi)^4} \frac{p^4 - 3p^2 m^2}{(p^2 - m^2)^2}, \quad (12)$$

The 4-boson vertex (A9) gives the bubble diagram, which yields upon contraction with a propagator

$$\Pi_\mu^\mu(0)_{\text{bubble}} = +6 \frac{g^2}{m^2} \int \frac{d^4 p}{(2\pi)^4} \frac{p^2 - 4m^2}{p^2 - m^2}. \quad (13)$$

The quartic terms cancel in the sum of the two diagrams, so the total vector boson self-mass is

$$\Delta m_{\text{self}}^2 = \frac{1}{4i} \Pi_\mu^\mu(0)_{\text{total}} = -\frac{3g^2}{16\pi^2} \int d^4 p \frac{p^2 - 2m^2}{(p^2 - m^2)^2} = \frac{3g^2 m^2}{16\pi^2}, \quad (14)$$

which is the same determinate integral found previously [3] for the photon mass. One sees that determinacy and degree of divergence are not related. Substituting the value of the

integral, the final result is a determinate self-mass correction

$$\Delta m_{\text{self}}^2 = -\frac{3g^2}{16\pi^2}m^2. \quad (15)$$

This term is absent when dimensional regularization is used to evaluate the integral.

The additional  $W^3W^3$  element of the neutral mass matrix transforms under the electro-weak rotation into

$$\Delta \mathbf{M}_{\text{self}} = -\frac{3m_W^2}{16\pi^2} \begin{pmatrix} g_e^2 & g_e g_Z \cos^2 \theta_w \\ g_e g_Z \cos^2 \theta_w & g_Z^2 \cos^4 \theta_w \end{pmatrix} \quad (16)$$

The self-interaction gives determinate contributions to all mass matrix elements found above.

There is also a self-correction to the  $W^\pm$  mass. It can be calculated in the same way, from the same Feynman diagrams with the result

$$\Delta m_{W\text{self}}^2 = -\frac{3g^2 m_W^2}{16\pi^2}. \quad (17)$$

The  $ZZ$  and  $W^\pm W^\pm$  self-terms contribute to the radiative corrections of the  $W/Z$  mass ratio. One can also find the same results by computing the vacuum polarization with the standard model Feynman rules.

The self-interaction gives a determinate extra photon mass term, and one sees that the fermionic and bosonic contributions to the photon mass have opposite sign, so they may cancel.

## 7. The mass sum rule

The determinate fermion and boson contributions to the photon mass have opposite sign. This may be seen as a consequence of the additional minus sign associated with a fermion loop. The photon mass will be zero when

$$m_t^2 = \frac{9}{8}m_W^2 + \text{other boson and fermion contributions}, \quad (18)$$

as found before [8] on basis of QED alone. The physical implications of this equation, when it is combined with the assumption of completeness of the standard model, will be discussed elsewhere [9].

The off-diagonal elements of the mass matrix do not cancel with the photon mass, so we are left with a two-particle  $A_\mu \leftrightarrow Z_\mu$  counterterm. This does not cause any problems since it is determinate. It cannot be helped while we do not possess a unified account of the electro-weak interaction.

Equation (18) is a special case of the more general boson/fermion mass sum rule derived previously [8] from QED alone.

$$\sum_{\text{fermions}} g_f q_f^2 c_j m_f^2 = \sum_{\text{bosons}} g_b q_b^2 c_j m_b^2, \quad (19)$$

The sums are to be taken over all fundamental fermions and bosons. The factors  $g_f$  and  $g_b$  are the multiplicity of the particles, and the  $q^2$ 's are the charges measured in units of the squared electron charge. The factors  $c_j$  are the relative coefficients of the integrals obtained from the vacuum polarization diagrams, to be calculated for each spin value. One finds  $c_j = 2J + 1$ , for  $J \leq 1$ , [8].

It is interesting to see that meaningful cancellation of bosonic and fermionic contributions to undesirable results may occur without invoking supersymmetry. There is a difference; with supersymmetry one hopes for cancellation of undesirable infinities, in the symmetrical theory of generalised functions applied to quantum field theory there are no infinities. Instead one has cancellation of physical predictions in disagreement with experiment.

It remains to be seen if the cancellation can be proved to all orders. There is good reason to believe that this is the case, since the results of generalised function calculations differ only by finite renormalizations from the results obtained by any standard regularization method. Any severe problems with the generalised function approach should be present in the standard account as well.

A mass sum rule such as (19) is as yet no constraint on the theory, as it can always be assumed to be satisfied. It is dominated by the heaviest particles, and one can always postulate as yet undiscovered, very heavy, new fundamental particles to close the sum rule.

Conversely, when the mass sum rule is known to hold, completeness of the physical theory may be surmised. This may constrain as yet unavailable theories of everything in the future. This point will be taken up elsewhere [9].

## 8. Radiative corrections and the existence of the Higgs boson

The radiative corrections computed by means of generalised functions differ from the same results calculated in the standard manner.

The relation between the vector boson masses and the weak mixing angle is not precisely given by (11). It is modified by higher order radiative corrections. It is customary to describe these by means of the  $\rho$ -parameter defined by

$$\rho := \frac{m_w^2}{m_z^2 \cos^2 \theta_w}. \quad (20)$$

In the standard treatment the second order correction to  $\rho$  is found to be [4]

$$\Delta \rho_{\text{standard}} = \frac{1}{4m_z^2} \Pi_\mu^\mu(0)_{ZZ} - \frac{1}{4m_w^2} \Pi_\mu^\mu(0)_{WW} = \frac{3g_w^2}{32\pi^2} \frac{m_t^2}{m_w^2}. \quad (21)$$

This expression has been evaluated using the standard Feynman rules, and dimensional regularization has been used to evaluate the integrals. Consequently only the axial part of the coupling contributes. The vector part is proportional to the usual photon mass integral, which is forced to be zero by the use of dimensional regularization.

In section (5) the finite terms were ignored. Actually this is not the correct way to handle the indeterminacy. Instead one has from (5) and (10)

$$m_z^2 \cos^2 \theta_w - m_w^2 = \frac{3g_w^2 m_t^2}{32\pi^2} \left(1 + \frac{8}{3} \sin^2 \theta_w - \frac{32}{9} \sin^4 \theta_w\right), \quad (22)$$

which is determinate and in agreement with the radiative correction [5] calculated before. In terms of the  $\rho$ -parameter [4] this translates to

$$\Delta\rho = \rho - 1 = \frac{m_w^2 - m_z^2 \cos^2\theta_w}{m_z^2 \cos^2\theta_w} = \frac{3g_z^2}{32\pi^2} \frac{m_t^2}{m_z^2} \left(1 + \frac{8}{3} \sin^2\theta_w - \frac{32}{9} \sin^4\theta_w\right). \quad (23)$$

The result of the generalised function calculation differs by a finite renormalization from the usual result [4] obtained by dimensional regularization. In the standard treatment one finds only the first term corresponding to the axial part of the generalised function result. Also the pre-factor contains  $g_z^2/m_z^2$  instead of  $g_w^2/m_w^2$ , but that is equivalent to this order.

The self-interaction of the weak vector bosons also contributes to  $\Delta\rho$ , since it contributes finite terms to both the  $W$  and  $Z$  mass. Substituting (16) and (17) one finds

$$\Delta\rho_{\text{self}} = -\frac{3g_w^2}{16\pi^2} (1 - \cos^4\theta_w). \quad (24)$$

Combining both contributions one finds to second order

$$\Delta\rho = \frac{3g_w^2}{64\pi^2} \left( \frac{m_t^2}{m_w^2} + \left( \frac{8m_t^2}{3m_w^2} - 8 \right) \sin^2\theta_w - \left( \frac{32m_t^2}{9m_w^2} - 4 \right) \sin^4\theta_w \right). \quad (25)$$

Finally, the standard model has a Higgs contribution to  $\Delta\rho$ . It is needed to obtain agreement with experiment, since it is the only negative contribution to  $\Delta\rho$  in the standard model. It has been evaluated to [4]

$$\Delta\rho_H = -\frac{3g_w^2 \sin^2\theta_w}{32\pi^2 \cos^2\theta_w} \ln \left( \frac{m_H}{m_z} \right). \quad (26)$$

In the generalised function treatment the self-interaction of the  $W$ - and  $Z$ -bosons also gives a negative  $\Delta\rho$ . Comparing the extra terms with the Higgs correction one finds the equivalent, to be added, Higgs mass

$$\Delta m_H = -m_z e^{1.9} \approx -600 \text{ GeV}, \quad (27)$$

which is no longer needed or allowed. The Higgs boson may be still have a mass close to  $m_z$ , but this seems to be excluded on other grounds.

The precision measurements of the radiative corrections, which are interpreted as evidence for the existence of the Higgs boson, may be reinterpreted as evidence for its non-existence in the generalised function approach. These limits have large experimental errors at present. They will be strengthened considerably in the near future when accurate measurements of the  $W$  mass become available at LEP.

Note: These remarks are preliminary as yet. The LEP experiments have been interpreted using formula dependent on dimensional regularization. The interpretation of the experimental results may therefore contain second order errors. It will be necessary to redo the analysis of the data, using the generalised function results, before firm conclusions can be drawn. It is a challenge to see whether the LEP precision data can be fitted to the theory without the Higgs mass, so effectively with one free parameter less.

## 9. Conclusions

To lowest order the effective Lagrangian for the electro-weak sector of the standard model has been derived from the computation of radiative corrections. The gauge boson masses appear naturally and inevitably, with the correct mass ratio. There is no need to postulate a Higgs mechanism. The electro-weak Lagrangian appears with the standard model couplings. The fermion masses remain arbitrary for the time being.

The recomputed radiative corrections probably leave no room for a Higgs contribution, but this will not be definite until the  $W^\pm$  mass has been measured to high precision. The data analysis will have to be corrected for use of formulae dependent on the use of dimensional regularization.

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## Appendix

Note: The integrals were computed in [3] with the convention  $g_{\mu\nu} = (-, +, +, +)$ . The sign changes needed for the modern convention  $g_{\mu\nu} = (+, -, -, -)$  are easily added. The integrals we need are

$$\int d^4p \frac{1}{(p^2 - a^2)^2} = -i\pi^2(\log a^2 + C), \quad (\text{A1})$$

$$\int d^4p \frac{p^2}{(p^2 - a^2)^2} = -i\pi^2 a^2(2\log a^2 + 2C - 1), \quad (\text{A2})$$

with  $C$  the indeterminate constant, and the  $i\epsilon$  in the denominator understood. Purists may read  $\log a^2$  as  $\log a^2/M^2$ , with  $M$  an arbitrary unit of mass, but this does not influence any physical result. The  $C$  convention has the mnemonic advantage that the rules for handling the  $C$  are the same as those of the  $C$  in the indefinite integral.

The general vertex factor is used in the form

$$\text{vertex} = -i\frac{g}{2}\gamma^\mu(c_V - c_A\gamma^5). \quad (\text{A3})$$

The unmixed Lagrangian vertex factors are

Particles	$g$	$c_V$	$c_A$
$t\bar{t}B_\mu$	$g'$	$\frac{5}{6}$	$-\frac{1}{2}$
$b\bar{b}B_\mu$	$g'$	$-\frac{1}{6}$	$\frac{1}{2}$
$t\bar{t}W_\mu^3$	$g_w$	$\frac{1}{2}$	$\frac{1}{2}$
$b\bar{b}W_\mu^3$	$g_w$	$-\frac{1}{2}$	$-\frac{1}{2}$

(A4)

After the electro-weak rotation one finds the standard vertex factors

Particles	$g$	$c_V$	$c_A$
$t\bar{t}A_\mu$	$g_e$	$2q_t = \frac{4}{3}$	0
$b\bar{b}A_\mu$	$g_e$	$2q_b = -\frac{2}{3}$	0
$t\bar{t}Z_\mu$	$g_Z$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_w$	$\frac{1}{2}$
$b\bar{b}Z_\mu$	$g_Z$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_w$	$-\frac{1}{2}$

(A5)

Finally the charged vertices are not affected by electro-weak mixing

Particles	$g$	$c_V$	$c_A$
$e\nu W_\mu^\pm$	$g_w/\sqrt{2}$	1	1
$tb W_\mu^\pm$	$g_w/\sqrt{2}$	1	1

(A6)

All calculations are performed in the unitary gauge, with propagators

$$\Delta_f^{\mu\nu}(k^2) = \frac{1}{m^2} \frac{m^2 g^{\mu\nu} - k^\mu k^\nu}{k^2 - m^2} \quad (\text{A7})$$

for the massive vector bosons. All three-boson vertices have the general form

$$\text{3-vertex} = ig(g_{\mu\nu}(p_3 - p_1)_\sigma + g_{\rho\sigma}(p_1 - p_2)_\mu + g_{\mu\sigma}(p_2 - p_3)_\rho). \quad (\text{A8})$$

The 4-boson vertex factor is

$$\text{4-vertex} = -ig^2(2g_{\mu\nu}g_{\rho\sigma} - g_{\mu\rho}g_{\nu\sigma} - g_{\mu\sigma}g_{\nu\rho}). \quad (\text{A9})$$

Only the coupling constant is different in different cases.

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